

Out-of-Ground-Effect Hover Performance of the UH-60A

SUMMARY

Five different flight test programs to measure the Out-of-Ground Effect (OGE) hover performance of a UH-60A helicopter have been reviewed, to determine the consistency of the flight test data. With one exception, these data fall into two groups: data obtained on the original utility configuration, and data for the 6th-year aircraft and beyond that include the Extended Stores Support System (ESSS) fairings. The one exception is the original production validation test, which agrees with the ESSS fairing data group, rather than the original utility group. The performance difference between the aircraft with and without the ESSS fairings is equivalent to a 3% increase in power or a 2% decrease in thrust. There is no clear or obvious explanation for this performance difference.

Factors that affect performance measurements are also examined, using data obtained from the UH-60A Airloads Program. It is shown that hover data are in general unsteady, but this unsteadiness occurs at high frequency and probably does not affect performance measurements. Detailed wind measurements made during hover testing on the Airloads Program show that winds at the test altitude may not be correlated with ground measurements, and a test criterion based on winds at ground level should be reassessed. Biases in power measurement have been identified for the UH-60A aircraft and it is now known that these biases are systemic to the UH-60 fleet. These biases are of the order of 4-5% in power, but their source is not known.

INTRODUCTION

Out-of-ground effect (OGE) hover of helicopters is normally considered a steady condition from a performance perspective. However, this approximation ignores a number of problems including: (1) the difficulty of obtaining truly steady flight on the vehicle, in part because the helicopter is unstable in hover; (2) the difficulty of obtaining data under zero wind conditions; (3) the fact that the rotor wake is fundamentally unstable in hover even for truly steady vehicle conditions (Caradonna et al. 1999); and (4) problems encountered in obtaining accurate measurements of performance parameters.

The U.S. Army Aviation Technical Test Center (ATTC), at Fort Rucker, AL, and, in a previous incarnation as the Aviation Engineering Flight Activity (AEFA) at Edwards AFB, CA, has obtained extensive hover performance data on the UH-60A since the 1970s. Table 1 lists the test reports that include hover performance measurements, up through the 12th-year production aircraft. The full citations for the test reports are in the reference list. These data are reviewed in this Occasional Note, in part, to judge the consistency of these data and, in part, to provide reference hover conditions for comparison with UH-60A Airloads Program data (Kufeld et al. 1994). In addition, other factors that may affect helicopter hover testing are reviewed, based on testing accomplished during the UH-60A Airloads Program, including (1) the effects of unsteadiness in airloads, (2) the influence of uncorrelated wind speed and direction

Table 1. – Hover performance test reports for the UH–60A through the 12th-year production aircraft.

CITATION	DATE	PROJECT NO.	AIRCRAFT
Yamakawa et al.	October 1979	77-23	77-22716
Nagata et al.	September 1981	77-17	77-22716, 77-22717
Williams et al.	May 1984	82-15-1	77-22716
Marshall et al.	June 1985	83-24	77-22716, 82-23748
Nagata et al.	January 1989	87-32	88-26015

at the ground and the test altitude, and (3) unresolved power measurement biases on the UH–60 helicopter.

DISCUSSION

OGE Hover Performance Data

The hover performance data presented in the reports listed in Table 1 were obtained using a tethered hover test technique in winds of less than three knots as measured on the ground. The tethered hover test technique offers two significant advantages over hover testing without a tether. First, the pilot is able to ensure that all three components of inertial velocity are near zero, as the tether constrains the aircraft to the surface of a hemisphere centered on the tether ground connection point and there are sufficient cues to keep the aircraft stationary at the top of this hemisphere. Second, a wide range of thrust coefficients can be obtained in one test as the pilot can operate the aircraft from tether forces near zero, at low power, up to tether forces where the aircraft is at full power.

Rotor thrust in hover is generally given as the non-dimensional thrust coefficient, C_T , or the thrust coefficient over the rotor solidity, C_T/σ . The rotor thrust is composed of

$$T = GW + F_{tether} + DL \quad (1)$$

where gross weight, GW , is the aircraft weight, F_{tether} is the tether force, and DL is the download on the fuselage. For performance testing, the aircraft weight is measured with scales prior to the flight and the fuel burnoff is measured during the flight so that the actual vehicle weight is known for each test point. The tether is connected to the ground through a calibrated load cell, so the tether force is also known. However, the download, DL , is not measured and generally is not included in hover performance measurements. Thus, for the performance measurements obtained by AEFA, the thrust used in calculating C_T includes only the gross weight and the tether force. Balch (1985) has reported download measurements from a number of model tests and the download can be expressed as a fraction of rotor thrust. For a UH–60A model the download varied from 4.5% at $C_T/\sigma = 0.05$ to 3.0% at $C_T/\sigma = 0.10$ (Balch 1985).

For UH–60A performance testing, power has been measured at a number of locations on the drive train. These power measurements are shown by the power balance equation

$$SHP_e - SHP_a - \frac{1}{\eta}(SHP_r + SHP_{tr}) = 0 \quad (2)$$

where SHP_e is the engine output power (both engines in the case of the UH–60A), SHP_a is the accessory power, SHP_r is the main rotor power, and SHP_{tr} is the tail rotor power. Gearbox

efficiency is included in η . The power balance in Eq. (2) is written at the input to the main gearbox so that the gearbox efficiency multiplies the main rotor and tail rotor powers. For the UH-60A, tail rotor power is measured on the output shaft from the main gearbox—if it was measured at the tail rotor it would be necessary to include the tail rotor intermediate and 90 deg gearbox efficiencies. All of the powers indicated in Eq. (2) were measured during AEFA performance testing except for accessory power. The calculated C_P was based on the engine output power, SHP_e .

The hover performance data in the AEFA reports is presented as C_P as a function of C_T . Generally, the data have been fitted with a function based on powers of C_T

$$C_P = a_0 + a_1 C_T^{1.5} + a_2 C_T^3 \quad (3)$$

where, ideally, a_0 and a_2 are zero and a_1 is unity. In some cases the standard error of estimate of C_P is provided. An example of one of these curves is given in Fig. 1. The baseline fit, in this case, is

$$C_P = 6.0892 \times 10^{-6} + 1.0304 C_T^{1.5} \quad (4)$$

and the computed standard error of estimate for C_P is 7.95×10^{-6} . The limited scatter seen in

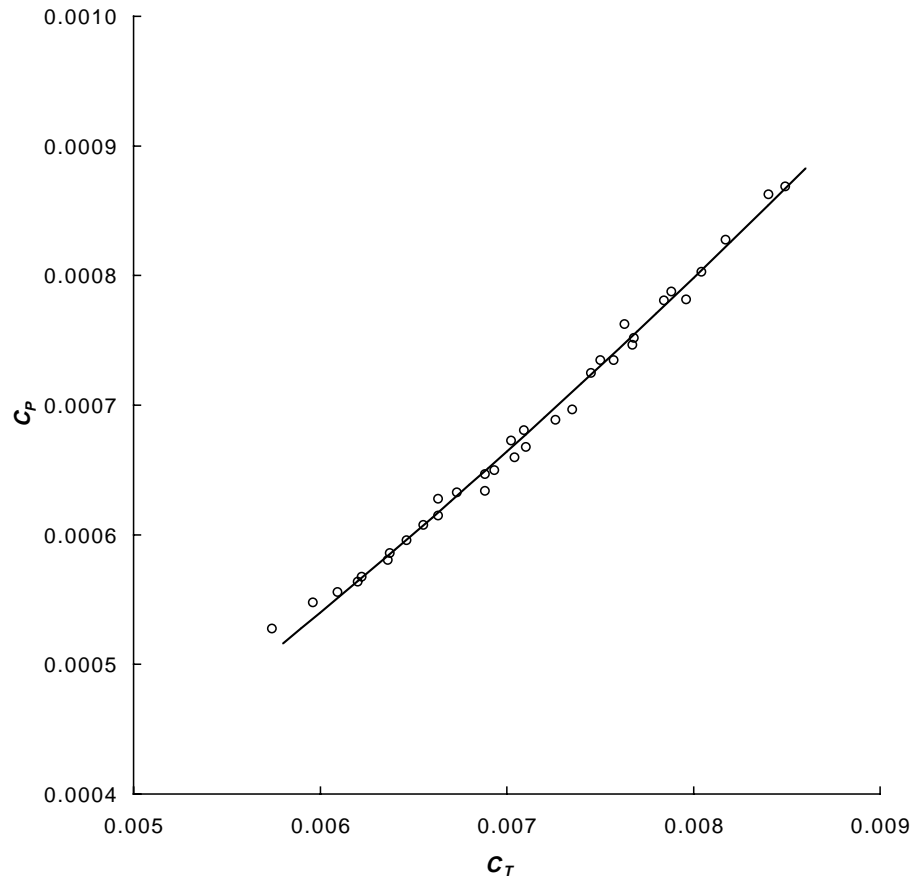


Figure 1. – Hover performance for 1st-year production UH-60A at density altitudes near 2160 feet (Nagata et al. 1981).

these measurements is quite good.

The best fits of the hover performance data from the tests listed in Table 1 are shown in Fig. 2. What is most apparent from this figure is that the performance data fall into two groups. The first group includes a test of a 1st-year production aircraft by Nagata et al. (1981) and a subsequent test of the same aircraft by Williams et al. (1984). The second group is made up of data from a test of a 1st-year production aircraft with the Extended Stores Support System (ESSS) fairings installed, the 6th-year production test by Marshall et al. (1985), the 12th-year production test by Nagata et al. (1989), and, curiously, the original production validation test by Yamakawa et al. (1979), on a 1st-year aircraft. The ESSS fairings are standard equipment on the 6th and subsequent year aircraft. The difference between these two groups of data is about 3% in power and 2% in thrust. The coefficients for the fits are shown in Table 2.

Production Validation Tests (Yamakawa et al. 1979). These tests were performed to determine whether the aircraft achieved the performance required under the development contract. The OGE hover performance was measured for a range of weight coefficients, while level flight

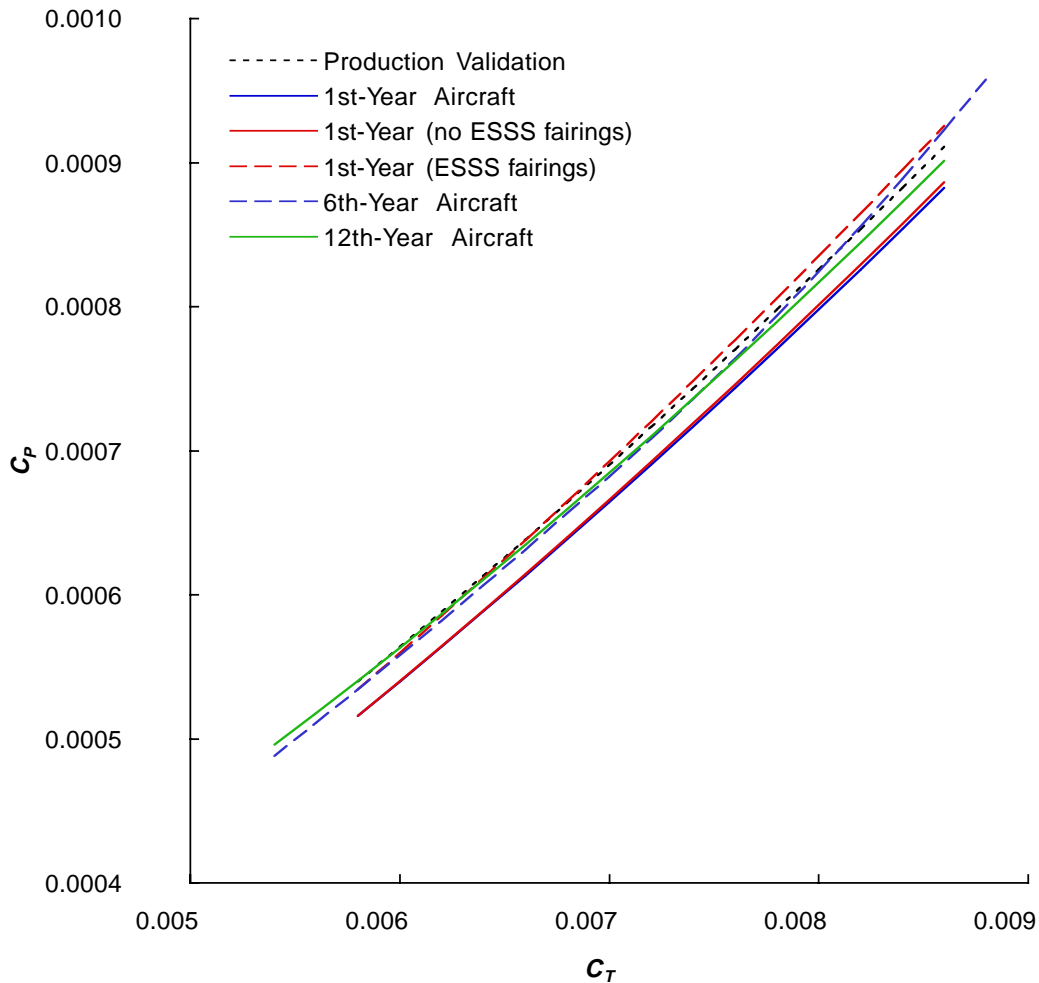


Figure 2. – Hover performance comparison for five different test programs.

Table 2. – Coefficients of fit for OGE hover performance for various AEFA tests of the UH–60A.

TEST	a_0	a_1	a_2	COMMENTS
Yamakawa et al. (1979)	7.846×10^{-5}	1.0443	0.0	
Nagata et al. (1981)	6.0891×10^{-5}	1.0304	0.0	$+\Delta C_p$ (see text)
Williams et al. (1984)	5.62345×10^{-5}	1.04093	0.0	no fairings
Williams et al. (1984)	4.86490×10^{-5}	1.09944	0.0	ESSS fairings
Marshall et al. (1985)	8.06470×10^{-5}	1.02707	0.0	
Marshall et al. (1985)	2.57292×10^{-4}	0.423840	515.0	$>70 \times 10^{-4}$
Marshall et al. (1985)	8.06470×10^{-5}	0.993090	0.0	(Nagata et al. 1981)
Marshall et al. (1985)	2.55577×10^{-4}	0.395715	510.0	$>70 \times 10^{-4}$ (Nagata et al. 1981)
Nagata et al. (1989)	1.13155×10^{-2}	0.9405	60.0	

performance data were acquired only for a single weight coefficient. The aircraft used was the third production aircraft. Tethered hover testing was performed at El Centro, CA (-47 feet) and Bishop CA (4120 feet).

The fit of all the hover data obtained in this test is shown in Table 2 and the associated standard error of estimate is 13.2×10^{-6} , about twice the scatter that was obtained in the later test data shown in Fig. 1. The Production Validation Test data were also fitted with a higher order equation

$$C_p = 2.7479 \times 10^{-4} + 0.40127 C_T^{1.5} + 518.30 C_T^3 \quad (5)$$

with a standard error of estimate of 12.7×10^{-6} . For contractual purposes, only the data from the Bishop OGE hover tests were used, and the fit in this case was

$$C_p = 2.9975 \times 10^{-5} + 1.1178 C_T^{1.5} \quad (6)$$

with a standard error of estimate of 13.2×10^{-6} . Although the coefficients from Eq. (5) and (6) are different than the nominal fit in Table 2, the actual curves differ only slightly (not shown).

1st-Year Production Test (Nagata et al. 1981). The basic purposes of this test were to obtain data for the Operator's Manual as well as to determine compliance with the Prime Item Development Specification. The two vehicles tested were the third and fourth production aircraft. OGE hover testing was performed at Edwards AFB, CA (2302 feet), Bishop CA (4120 feet), and Coyote Flats, CA (9980 feet).

Testing at the three different altitude sites resulted in three different sets of data and three different curve fits. The coefficients shown in Table 2 are based on the data taken at Edwards AFB (see also Fig. 1). Graphical corrections for flight at higher altitudes were computed (see Fig. 6, Nagata et al. 1981) but no analytical form for the ΔC_p corrections were provided. No standard errors of estimate were given.

The improved OGE hover performance of the 1st-year production aircraft in these tests with respect to the production validation tests of Yamakawa et al. (1979) was noted by Nagata et al. They reported that the performance increase was about 1.3%, however, this is less than the increase shown in Fig. 2. They noted that there were “unexplained discrepancies between the PVT-G and A&FC hover results. However, some differences may be attributed to the C_T range, rotor speed, wheel heights, and site elevations.”

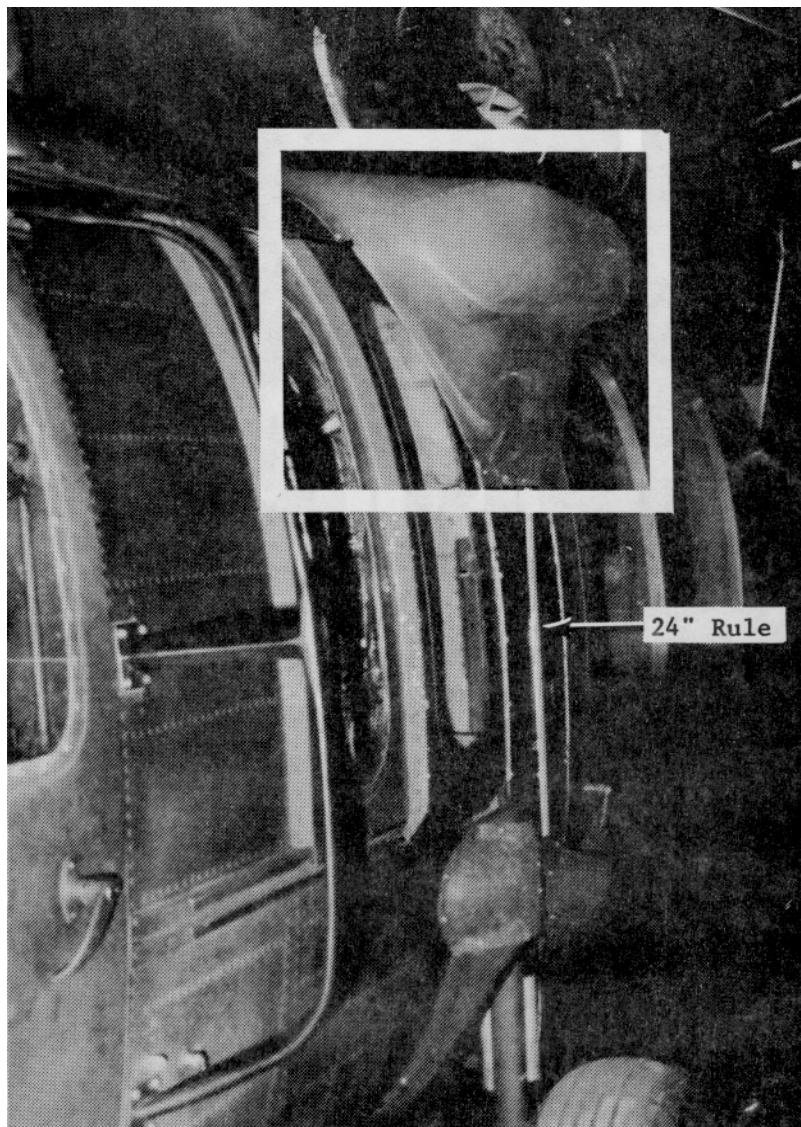


Figure 3. – Upper ESSS fairing installed on test aircraft (Williams et al. 1984).

Effects of ESSS Fairings (Williams et al. 1984). An Extended Stores Support System (ESSS) was developed for the UH-60A, to allow for self-deployment. Hardpoints were added to the aircraft to support the ESSS and, with the ESSS removed, these hardpoints were covered with aerodynamic fairings. Initial tests of this configuration indicated an excessive increase in both the flat plate drag area and a reduction in hover performance. Therefore, an additional test was established using a 1st-year production aircraft with and without ESSS fairings. For this test the fairings were hand made of fiberglass and they showed slight shape differences and an improved surface finish over the production versions (tested later by Marshall et al. 1985). The upper ESSS fairing on the left side of the aircraft is illustrated in Fig. 3.

OGE hover testing was performed primarily using the tethered hover technique at Edwards AFB, CA. The measured OGE hover performance without the fairings was very similar to the results of Nagata et al. (1981). With the fairings installed, there was an increase

in the power coefficient of 4% and a thrust coefficient loss of about 2.7%. The cause of this performance loss is not known. A download increase of approximately 50% would be required to explain the 2.7% reduction in the thrust coefficient. The coefficients used to fit the two data sets are shown in Table 2. No standard error of estimate was provided for these fits.

6th-Year Production Aircraft Test (Marshall et al. 1985). The primary objective of this test was to obtain flight data to update the Operator's Manual for the 6th-year production aircraft. Two aircraft were tested: a 6th-year production aircraft and a 1st-year production aircraft that had been modified to include some of the updates to the 6th-year production configuration. Hover performance data using the tethered hover technique were obtained at Edwards AFB, CA (2302 feet), Bishop CA (4120 feet), and Coyote Flats, CA (9980 feet).

The hover performance data on the 6th-year production aircraft, which includes the production ESSS fairings, agree quite well with the data from Williams et al. (1984), see Fig. 2; the differences are less than 1% in thrust. A two segment fit of the hover data was used, as indicated in Table 2. Marshall et al. also re-analyzed the data from Nagata et al. (1981) for the 1st-year production aircraft, again using a two-segment fit (see Table 2). Their re-analysis allowed them to include all of the test data without using a ΔC_P correction based on pressure altitude. They recommended in their report that this fit be used in the Operator's Manual for the 1st-year aircraft. Comparing the 1st- and 6th-year production OGE hover data, there is a 3% increase in power required or an equivalent 2% reduction in thrust.

12th-Year Production Aircraft Test (Nagata et al. 1989). The primary objective of the testing of the 12th-year production aircraft was to obtain baseline data for this configuration. A 12th-year aircraft was used for these tests and OGE hover data were obtained at a single elevation at Edwards AFB, CA (2302 feet). The performance data are shown in Fig. 2 and the coefficients of the fit are shown in Table 2. Good agreement is seen between this data set and the 6th-year data.

The three sets of data shown in Fig. 2 for the test aircraft with the ESSS fairings installed show good agreement with each other. At lower thrust coefficients the best fit equations agree to within 0.5% in thrust. At higher thrust coefficients the agreement is not as good and range from 1 to 2% in thrust. The discrepancies at higher thrust coefficients may be related to the different test elevations used for these tests. Marshall et al. (1985) obtained their data at three elevations, from 2302 to 9980 feet. The other two data sets were obtained at one location, Edwards AFB, at 2302 feet. The two data sets for the 1st-year production aircraft (without ESSS fairings) also show good agreement. However, the production validation test data do not fit this pattern and lie between the values observed for the later tests with the ESSS fairings. A special-purpose instrumented inlet was used for the production validation tests and this is shown in Fig. 4. Yamakawa et al. (1979) comment that these "inlets did not mate well with the rest of the airframe." Whether the poor fit of the special-purpose inlet affected these measurements is unknown.

The disagreement of the Yamakawa et al. (1979) data with the other data sets and the effects of the ESSS fairings on hover performance are not readily explained. The measured effects of the fairings, particularly from the back-to-back tests of Williams et al. (1984), show a decrease in rotor thrust of roughly 2% which, if solely caused by download, would be an increase in fuselage download of about 50%. In terms of projected area, the fairings should have only a minor affect on the download, perhaps an increase in vertical drag of 5%, rather than the value of 50% that would be required to explain the discrepancy in hover performance. The resolution of this problem is unknown.



Figure 4. – Fit of special-purpose instrumented inlet on production validation OGE hover test (Yamakawa et al. 1979).

Hover Unsteadiness

Although OGE hover is normally considered a steady condition, there is a certain amount of unsteadiness in part because of the difficulty of stabilizing a flight vehicle with unstable modes and also because the rotor wake is fundamentally unstable (Caradonna et al. 1999). Some insight into this unsteadiness can be obtained from blade airloads measured during the UH-60A Airloads Program. During the ground-acoustic test phase of the Airloads Program, the aircraft's inertial velocities were accurately measured with laser and radar trackers and the air mass velocity was measured with a variety of instruments, including wind speed and direction measurements at ground level as well as on a tethered balloon at the test altitude. The combination of these measurements allowed an accurate calculation of the relative velocity between the aircraft and the air mass.

The integrated normal force, based on pressure measurements on the UH-60A rotor blade at nine radial stations, is shown in Fig. 5 for the most stable condition obtained during the Airloads Program. The measured normal forces at the radial stations are offset in Fig. 5 to better show each station's normal force. For this case, the advance ratio was of the order of 0.001 (0.5 knots). The data show reduced lift on the outboard section of the blade at the

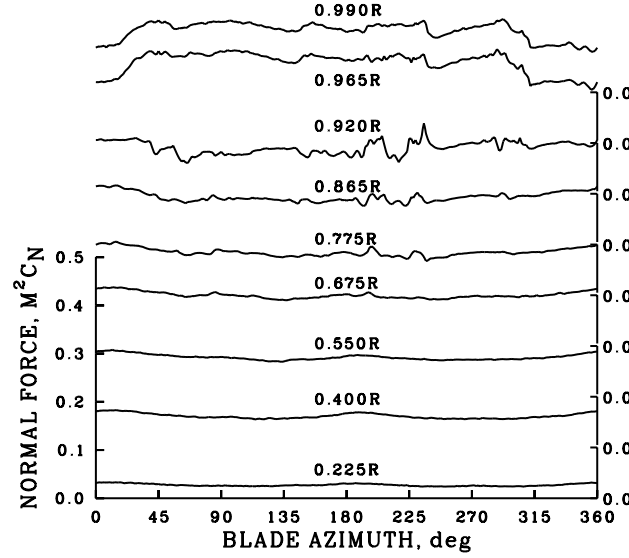


Figure 5. – Normal force measured at nine radial stations on the UH-60A rotor in hover; $\mu_x = 0.001$, $\mu_y = 0.000$ (Counter 9605).

empennage location, which is expected. What is not expected, perhaps, is the unsteadiness in the normal force that is seen at some of the outer radial stations. The angle-of-attack excursions associated with the changes in normal force shown in the figure can be approximated as

$$\Delta\alpha \approx \frac{1}{2\pi\beta} \Delta C_N \quad (7)$$

where $\beta = \sqrt{1 - M^2}$. The angle-of-attack change observed at 0.92R for this case is about 2.7 deg. Angle-of-attack variations of this size in hover are likely caused by a rotor wake tip vortex moving up into the rotor disk and intersecting a blade. Hence, even under steady conditions there is some limited unsteadiness, apparently caused by in the rotor wake.

The unsteadiness in the measured airloads is increased in a case with relative motion between the aircraft and the air mass. With the relative wind from the right quadrant, the unsteadiness is increased in the fourth quadrant, as shown in Fig. 6. The angle-of-attack variations for this latter case range from 2.8 to 3.1 deg on the outer blade and, again, this is likely caused by tip vortices convecting across the rotor disk.

It appears, therefore, that even in the best of conditions a certain amount of unsteadiness is inherent in the blade airloads. However, these fluctuations in blade lift occur at higher frequencies and probably have little effect upon the steady or average value of the rotor thrust. In addition, the use of repeated test points will likely compensate for the random nature of this unsteadiness.

Measurement of Wind Velocity and Airspeed at Altitude

Standard flight test practice requires that hover performance testing be conducted in winds at ground level of less than three knots. However, measurements made during the Airloads Program suggests that even this restrictive criterion may not be sufficient. During the ground-acoustic testing part of the program, measurements of air mass velocity were made at a number of altitudes and these measurements were not always well correlated, as shown in Fig. 7. Ground winds on Flight 93 were less than three knots, but the winds at the test altitude of 250 feet were about seven knots, because of the development of a strong shear layer near 100

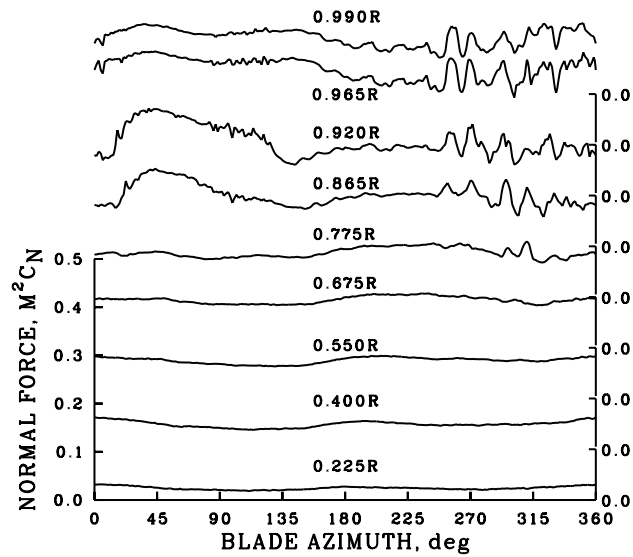


Figure 6. – Normal force measured at nine radial stations on the UH-60A rotor in hover; $\mu_x = -0.018$, $\mu_y = 0.015$ (Counter 9406).

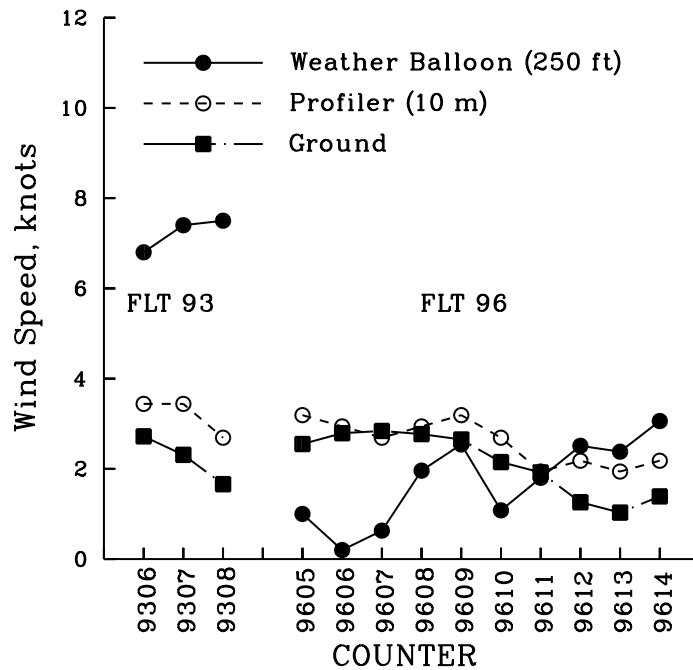


Figure 7. – Measured wind speeds at three altitudes obtained during hover testing on flights 93 and 96; UH-60A Airloads Program.

feet on that day. On Flight 96, however, the ground winds were all less than three knots and, for most of these test conditions, the winds at the test altitude were also below three knots. This suggests that measurements of the air mass velocity at the aircraft test altitude are needed to provide the proper criterion for still air conditions when making performance measurements.

Rotor Power Measurement Anomalies

The power obtained in hover performance tests is susceptible to a variety of measurement errors. In general, the power used in calculating the power coefficient is not the main rotor power, but rather is the engine output power or total system power. The relationship between the various powers for a typical aircraft was previously shown in Eq. (2). In looking at the power balance equation it is useful to group the measured terms on one side of the equation and the unmeasured terms plus all measurement errors on the other side, that is,

$$\Delta_A = SHP_a + \varepsilon = SHP_e - \frac{1}{\eta}(SHP_r + SHP_{tr}) \quad (8)$$

The term Δ_A is termed the power loss and, if the measurement errors, ε , were zero, would be identical to the accessory power. The variation of the power losses has been previously examined in Occasional Note 1999-04 for all of the level flight testing done under the UH-60A Airloads Program. Surprisingly, the power losses (and hence errors) are much greater than the expected accessory power of about 65 HP. Figure 4 from ON 1999-04 is reproduced here as Fig. 8 and shows power loss values that range from -40 to 180 HP. As shown in Fig. 8, the power loss (error) depends upon the measured outside air temperature and, based on a linear regression model, 80% of the variance is explained by the outside air temperature.

The power losses (errors) in Fig. 8 are caused by errors in either the engine output torque measurement, the main rotor torque measurement, or both. The size of these errors is too great to be explained by errors in the measurement of tail rotor power or gearbox efficiency. If the error is completely in the engine torque output measurement, see Eq. (8), then the computed value of the power coefficient will be in error by the same amount. If the error is in the main rotor torque measurement, then the power coefficient results will be correct. Unfortunately, there is no way from the present data to determine the sources of these errors.

The power measurement errors shown here, using data from the UH-60A Airloads Program, are not an isolated case. An unpublished analysis of data obtained from testing of the Wide Chord Blades for the UH-60 have shown similar power measurement errors. These tests were performed on a different aircraft and represent an independent data set. In addition, these unpublished data indicate that there are unquantified drift and rotor speed effects on the power losses as well. The total effect of these errors, depending upon where they occur in the drive train, may account for an uncertainty as large as $\pm 4.5\%$ of engine power.

CONCLUSIONS

Multiple test programs to obtain Out-of-Ground Effect (OGE) hover performance with a UH-60A helicopter have been reviewed in this Occasional Note and, based on this review, the following conclusions are made.

1. Two tests of the original utility configuration, without the Extended Stores Support System (ESSS) fairings, show very good agreement.
2. Three tests of the UH-60A with the ESSS fairings also show good agreement, although compared to the original utility configuration, there is an approximately 3% increase in power or 2% reduction in thrust.
3. The original production validation tests of the UH-60A is anomalous, in that its performance matches the test data obtained with the ESSS fairings installed rather than the original utility configuration.

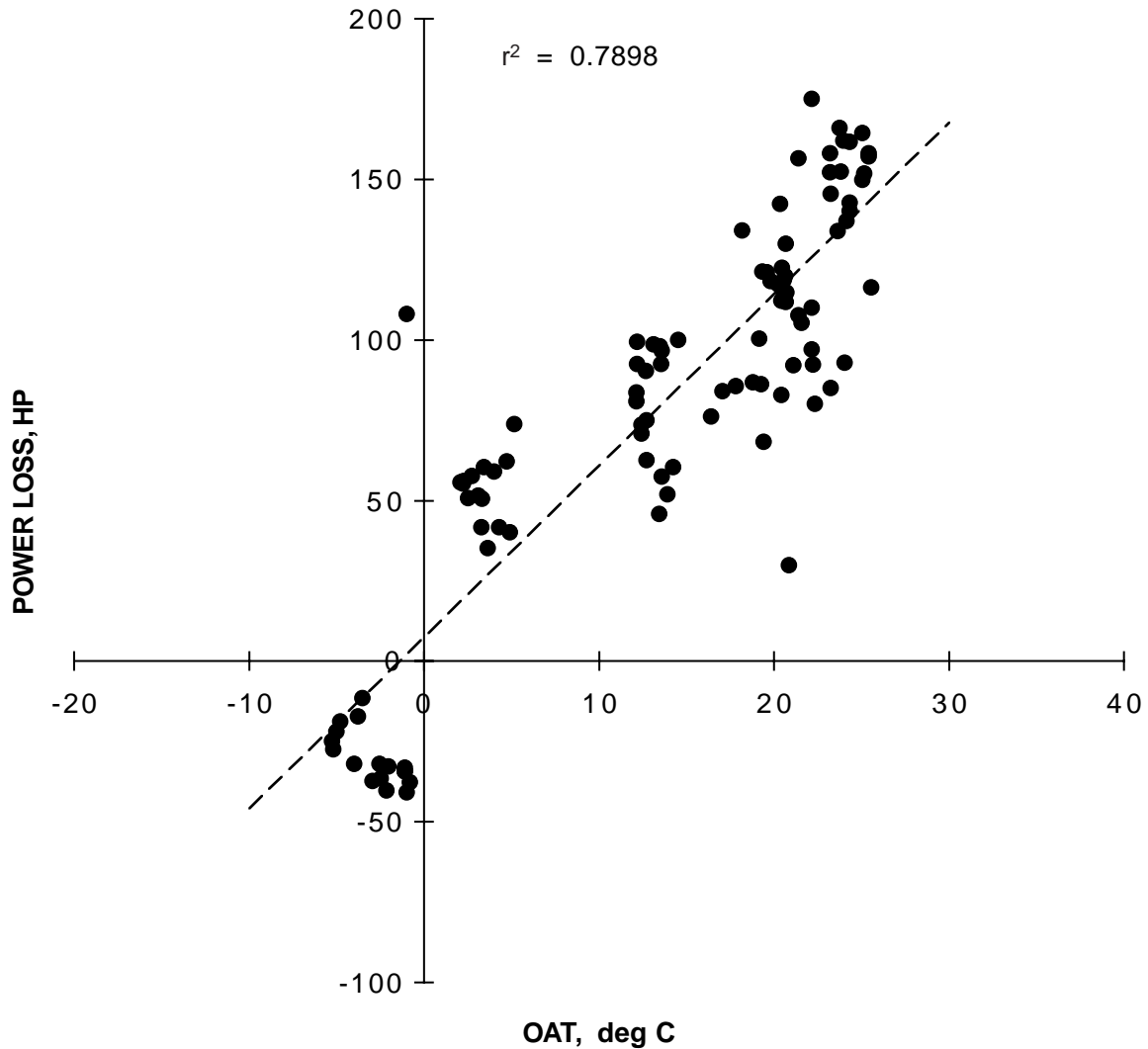


Figure 8. – Power losses for all level flight airspeed sweep points shown as a function of the outside air temperature (OAT); from Occasional Note 1999-04.

4. Performance differences between the aircraft with and without the ESSS fairings are not readily explained. An increase in fuselage download of approximately 50% would be required to explain the performance differences.

The accuracy of hover performance measurements is affected by a number of factors and some of these have also been reviewed in this Occasional Note. In this regard it is concluded that

1. Fundamental unsteadiness in the rotor wake, similar to that identified in model rotor tests, will also occur under flight conditions. However, this unsteadiness occurs at higher frequencies and is unlikely to have a significant influence on rotor performance measurements.

2. Based on test data obtained during the UH-60A Airloads Program, it is shown that winds at test altitude are not necessarily correlated with ground measurements. Thus, the criterion for hover testing only when ground winds are less than three knots requires re-examination.
3. There are unresolved power measurement biases for the UH-60 helicopter that can cause substantial inaccuracies in the measurement of power. The source of this biases is currently unknown.

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